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An experimental study on tuned liquid damper for mitigation of structural response

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Abstract

This paper investigates the performance of unidirectional tuned liquid damper (TLD) that relies upon the motion of shallow liquid in a rigid tank for changing the dynamic characteristics of a structure and dissipating its vibration energy under harmonic excitation. A series of experimental tests are conducted on a scaled model of structure-tuned liquid damper systems to evaluate their performance under harmonic excitation. One rectangular and one square TLD with various water depth ratios are examined over different frequency ratios, and time histories of accelerations are measured by precisely controlled shaking table tests. The behaviour of TLD is also studied by changing the orientation of the rectangular TLD subjected to the given range of harmonic excitation frequencies. The effectiveness of TLD is evaluated based on the response reduction of the structure. From the study, it is found that for each TLD, there exists an optimum water depth that corresponds to the minimum response amplitude, and the maximum control of vibration is obtained under resonance condition with the attachment of TLD.

Keywords: Harmonic excitation, Tuned liquid dampers, Liquid sloshing, Energy dissipation, Response control, Selection of TLD parameters

Introduction

Due to rapid urbanisation and industrialisation, there is an increasing demand of high-rise buildings. These buildings inspired the use of high-strength, light-weight materials and the increase in the use of welded connections and light facades that serve as exterior walls without contributing to the structural strength. These developments have led to the construction of flexible buildings with reduced structural damping. As a result, the sensitivity of these buildings to dynamic excitations such as earthquake and wind has increased. Thus, it is essential to search for vibration-suppressing devices to counteract undesirable vibration in the structures. These devices may be passive, active, semi-active or hybrid types. The passive device, tuned liquid damper (TLD), is a type of tuned mass damper (TMD) where the mass is replaced by liquid (generally water). A conventional TMD needs frictionless rubber bearings, special floor for installation, springs, dashpots and other mechanical components which increase the cost of this

device. However, the dead weight of the mass has no other functional use.

Although TLD is usually a rigid tank with shallow water in it, it promises to be most suitable, since existing water tanks in buildings may be used as TLD without adversely affecting its functional use and also include low cost and maintenance. The working principle of TLD is based on sloshing of the liquid to absorb a portion of the dynamic energy of the structure subjected to seismic motion and thus controlling the structural vibration.

Several research works have been carried out to find the applications of TLD in reducing the seismic vibration of the structure (Banerji et al. 2000; Banerji et al. 2010; Bauer 1984; Fujino et al. 1988; Koh et al. 1994; Modi and Welt 1988; Tamura et al. 1995). Sun et al. (1992) successfully developed an analytical model for TLD based on shallow-water wave theory. Based on this theory, Banerji et al. (2000) have conducted numerical studies on TLD and concluded that TLD can be very effective in reducing vibration of the structure if the design parameters are approximately set. Koh et al. (1995) studied the behaviour of rectangular liquid dampers under horizontal acceleration of arbitrary time history.

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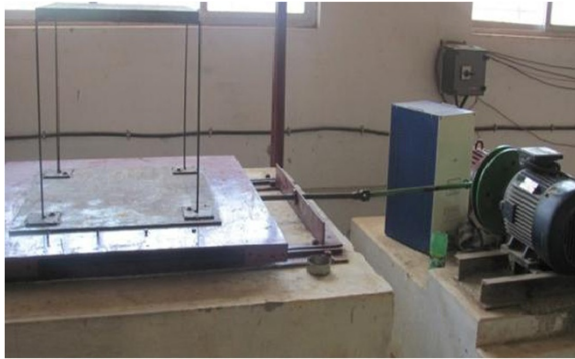


Figure 1 Experimental set-up.

The theoretical model to predict the motion of shallow liquid in a rectangular tank was developed for sinusoidal excitation, and numerically, they concluded that the effectiveness of dampers is dependent on the frequency content of the earthquake spectrum and the positions where the dampers are placed. Reed et al. (1998) investigated the behaviour of TLDs through laboratory experiments and numerical modelling. In his study, the major focus was the large-amplitude excitations, whereas most of the experimental works conducted in the past (Fujino et al. 1992; Koh et al. 1995) were for TLDs subjected to small-amplitude excitations. It is observed that the response of a TLD to large-amplitude excitations would be significantly different from that for small-amplitude excitations due to larger probabilities of surface-wave breaking occurrence.

The objectives of this study is to reduce structural response by installing a model of TLD attached to the structure subjected to sinusoidal external excitation and to study the effects of various parameters, which affect the structural response. These parameters include the ratio of water depth to tank length, called water depth ratio, the ratio of sloshing frequency to structural natural frequency, called tuning ratio, and the ratio of excitation frequency to natural frequency of the structure, called excitation frequency ratio.

Methods

Experimental set-up and procedure

Figure 1 shows arrangement of the structure over a uni-directional shaking table. The shaking table is arranged



Figure 2 TLD scale model performance test.

to impose horizontal motions on the structure. The size of the table in plan is 1×1 m, and it weighs approximately 140 kg. The range of maximum displacement is ± 100 mm. The maximum operating frequency is in between 0 and 10 Hz. The required excitation frequency is applied to the structure by means of a microprocessor-based three-phase precision AC drive. The TLD is placed centrally on the structure as shown in Figure 2. The TLD tanks are made up of acrylic sheet, having 4-mm-thick sidewalls and base plate. The structural model is made up of mild steel plate with enough thickness to ensure a rigid floor, supported on four high-tensile steel rods with a size of $6 \times 6 \times 500$ mm. The load on the slab is transferred to the columns through two cross beams having the same dimensions as the columns. The columns are connected to the slab and base plates by welding. The natural frequency of the structural model without tank was 1.9 Hz. The motion imposed on the structure is harmonic, with control over the amplitude and the frequency of the oscillations.

Table 1 TLD parameters

Case number	Type of TLD		Container dimensions		
	Shape	Symbol	Length (cm)	Width (cm)	Depth (cm)
Case 1	Rectangular	TLD ₁	30	20	30
Case 2	Rectangular	TLD ₂	20	30	30
Case 3	Square	TLD ₃	30	30	40

Table 2 Experimental cases

TLD type	Water depth ratio	Base displacement amplitude (mm)	External frequency (Hz)	Excitation frequency ratio (β)
TLD ₁	0.05, 0.1, 0.15, 0.2, 0.25, 0.3	3	1.4, 1.6, 1.8, 1.9, 2.0, 2.2, 2.3, 2.4	0.75, 0.85, 0.95, 1.0, 1.05, 1.15, 1.2, 1.3
TLD ₂	0.05, 0.1, 0.15, 0.2, 0.25, 0.3	3	1.4, 1.6, 1.8, 1.9, 2.0, 2.2, 2.3, 2.4	0.75, 0.85, 0.95, 1.0, 1.05, 1.15, 1.2, 1.3
TLD ₃	0.05, 0.1, 0.15, 0.2, 0.25, 0.3	3	1.4, 1.6, 1.8, 1.9, 2.0, 2.2, 2.3, 2.4	0.75, 0.85, 0.95, 1.0, 1.05, 1.15, 1.2, 1.3

In this study, the depth ratio (Δ) is defined as the ratio of water depth (h) to tank length (L) in the direction of shaking. The tuning ratio, which is defined as the ratio of fundamental sloshing frequency (f_w) to the natural frequency of the structure (f_s), is maintained by filling water up to the desired level in the TLD.

According to the linear wave theory given by Lamb (1932), the fundamental natural frequency of water sloshing motion, f_w , can be calculated as follows:

$$f_w = \frac{1}{2\pi} \sqrt{\left(\frac{\pi g}{L}\right) \tan\left(\frac{\pi h}{L}\right)}, \quad (1)$$

where, g = gravitational acceleration, h = still water depth and L = length of the tank in the direction of sloshing motion.

The excitation frequency ratio, β , which is the ratio of excitation frequency to structural natural frequency, is controlled by varying external frequencies.

The measured response parameters are displacement and acceleration of the structure along the direction of force. The displacement response is measured by attaching Brüel & Kjær Deltatron 4507–001 accelerometers (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark) at the base and top of the structure. PULSE 3560B computerised data acquisition and multi-analyser system is used to acquire and analyse the experimental data. In

each set of experiments, the TLD-structure system is subjected to harmonic sinusoidal base motions with different excitation frequencies. The external sinusoidal force is applied to the structure by means of an induction motor mounted on the shaking table. The external excitation amplitude is accordingly maintained constant by keeping the displacement amplitude of the shaking table constant.

Selection of TLD parameters

The response of a structure with a TLD attached and subjected to a base excitation will depend on the characteristics of the TLD-structure system. A TLD may be considered as properly designed if it significantly reduces a structure's response for a particular ground motion for a given set of values of water depth ratio, Δ , and excitation frequency ratio, β . In this study, the vibration reduction of the structure has been observed by considering different values of the water depth ratio, Δ , and several frequency ratios, β , which is shown in Tables 1 and 2.

Results and discussion

Investigations are conducted to study the dynamic behaviour of a structure with TLD when subjected to harmonic base motion given to the shaking table. The harmonic ground motion is defined by its excitation frequency and amplitude of ground motion. As the harmonic motion

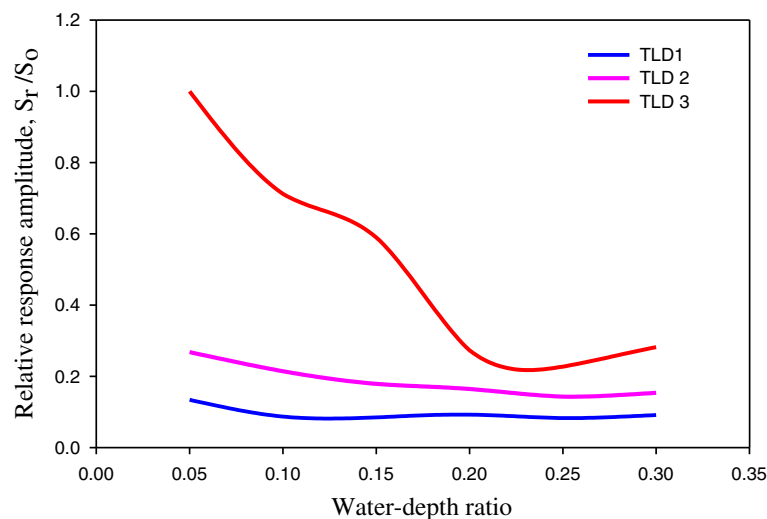


Figure 3 Structural response amplitude versus TLD water depth ratio in resonance condition.

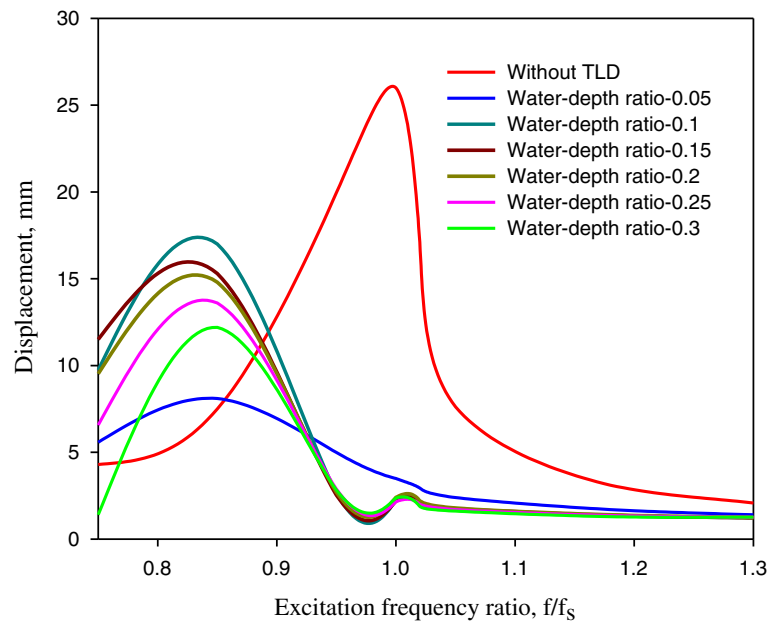


Figure 4 Displacement response of structure for varying frequency ratios with different water depth ratios for TLD₁.

consists of a single frequency, the study of the structure with TLD will provide an understanding of the behaviour of TLD-structure system for this kind of motion. In this study, displacement and acceleration of the structure with and without TLDs are measured by means of accelerometer and data acquisition system, considering various excitation frequencies. The results of this experimental study have been plotted as the relative response ratio as a function of water depth ratio and displacement as a function

of frequency ratio. Time versus acceleration graphs are also plotted for different conditions of TLDs.

Effect of water depth ratio on structural response

Different water depth ratios, which is water depth (h) to tank length (L), varying from 0.05 to 0.3 are considered, and corresponding maximum structural response has been shown in Figure 3. The three curves in Figure 3 show the relationship between the structural response

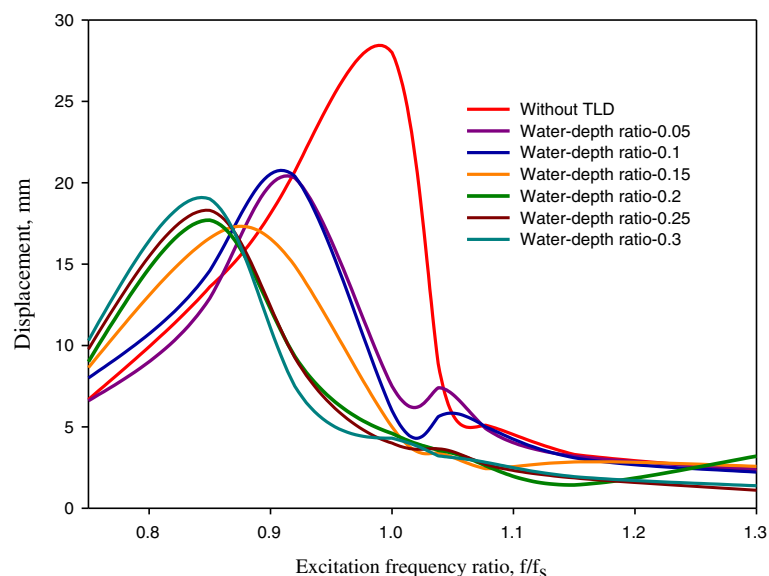


Figure 5 Displacement response of structure for varying frequency ratios with different water depth ratios for TLD₂.

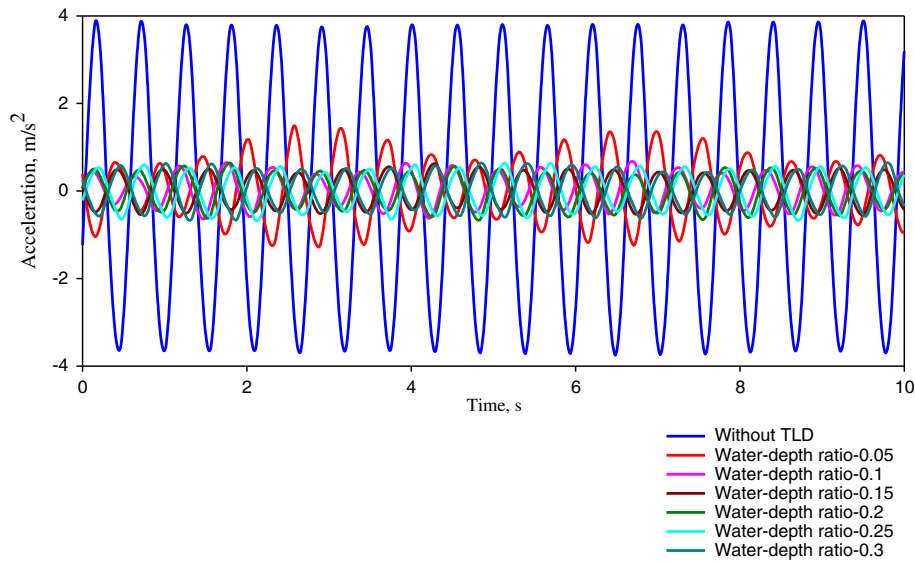


Figure 6 Time histories of structural acceleration with and without TLD (for TLD₁, $\beta = 0.95$).

amplitude in resonance condition and the corresponding water depth ratio in the three TLDs considered. The horizontal axis is the water depth ratio, and the vertical axis is the relative response amplitude S_r/S_0 , the latter being the ratio of maximum structural response amplitude with TLD to the maximum response amplitude without TLD. From Figure 3, it can be clearly observed that for each case, there exists optimum water depth that corresponds to the minimum response amplitude. These values are 7.5, 5 and 7.5 cm, respectively, for TLD₁, TLD₂ and TLD₃. From Figure 3, it is also observed that TLD₃, that is, the square TLD, is less effective in

comparison with TLD₁ and TLD₂, that is, the rectangular TLDs for controlling response of the structure. For this reason, further studies have been carried out with rectangular TLDs, that is, TLD₁ and TLD₂.

Effect of various external frequencies on structural response

The displacement response of the structure for various excitation frequency ratios with different water depth ratios has been shown in Figures 4 and 5. Several external frequency ratios ranging from 0.75 to 1.3 and water depth ratios ranging from 0.05 to 0.3 are considered in this

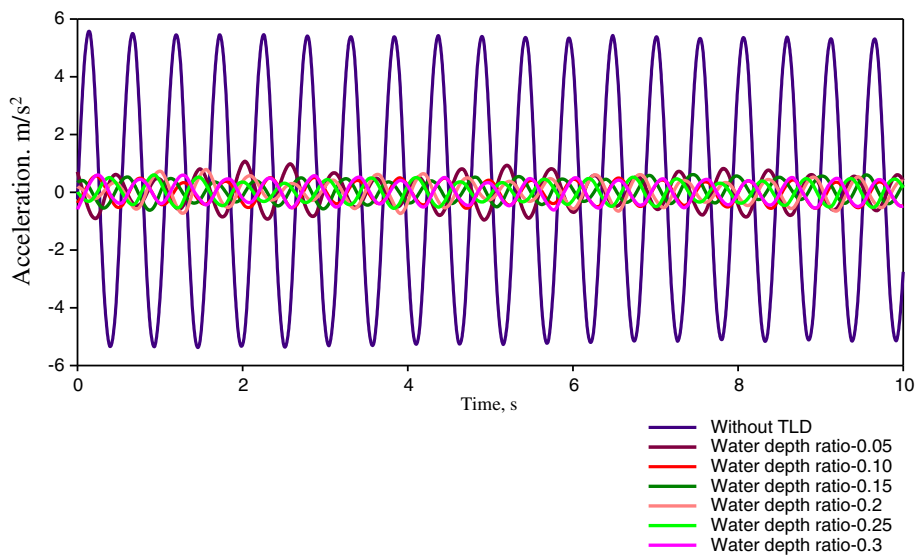


Figure 7 Time histories of structural acceleration with and without TLD (for TLD₁, $\beta = 1.0$).

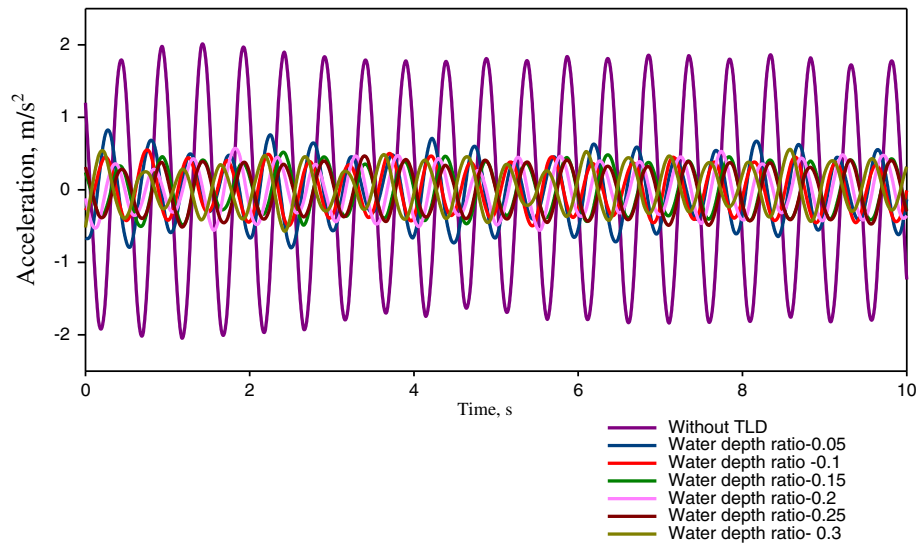


Figure 8 Time histories of structural acceleration with and without TLD (for TLD_1 , $\beta = 1.05$).

study, and the corresponding structural response has been observed. From Figures 4 and 5, it is easily observed that at the initial stage, when the excitation frequency is lower than the resonance frequency, the peak structural response typically increases with increasing water depth ratio. However, at the region of resonance ($f/f_s \approx 1$), the response amplitude reduces drastically upon attachment of the TLD. Similarly, when excitation frequencies become higher than the resonance frequency, no efficient control is observed. Thus, maximum control of response is obtained when the structure is subjected to resonance

frequency, and the reduction of response, considering the resonance condition, is obtained at nearly 86.6% and 73.2% for TLD_1 and TLD_2 , respectively.

Typical plots of acceleration time histories of structure for excitation frequency ratios (f/f_s) 0.95, 1 and 1.05 are shown in Figures 6, 7 and 8 for TLD_1 . In these cases, the acceleration response at the top of the structure has been observed, considering the varying water depth ratios. From Figure 6, it is seen that for the frequency ratio of 0.95, the maximum acceleration of the structure without TLD is as about 3.7 m/s^2 , which is reduced to

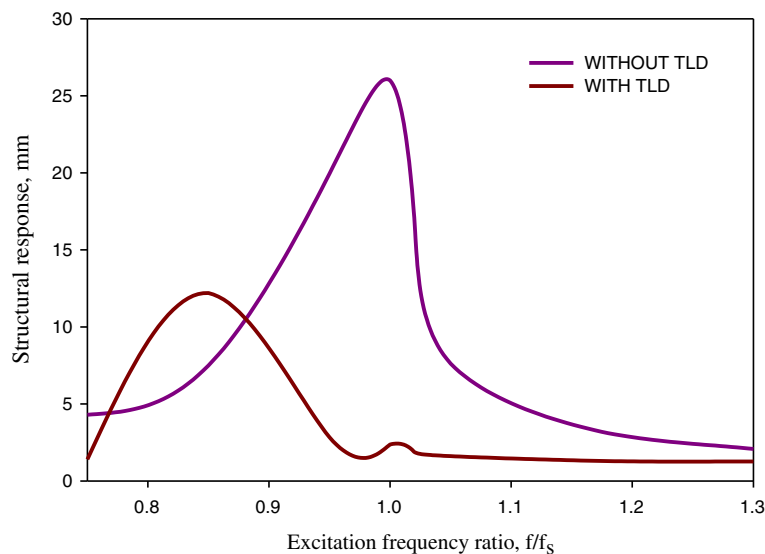


Figure 9 Displacement response for various excitation frequency ratios considering $f_w/f_s = 1$ for TLD_1 .

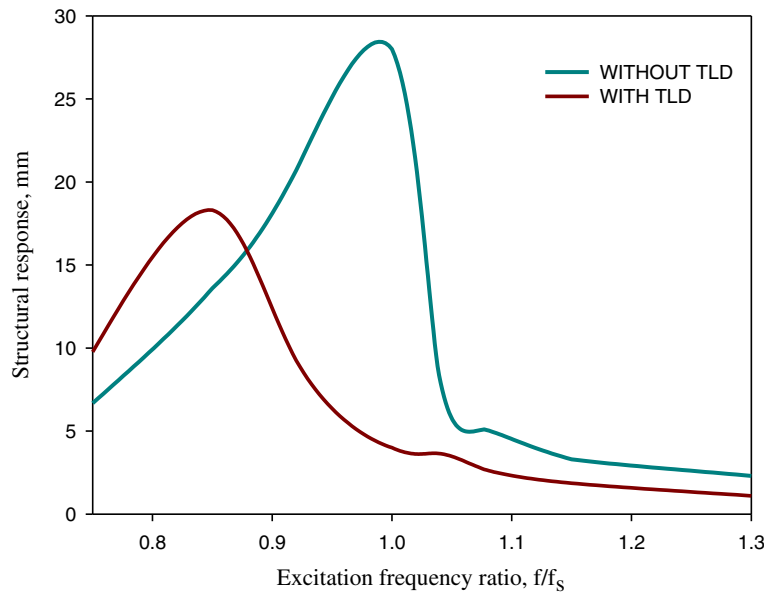


Figure 10 Displacement response for various excitation frequency ratios considering $f_w/f_s = 1$ for TLD₂.

nearly 1.4 m/s^2 for the water depth ratio of 0.05 and within the range of 0.4 and 0.6 m/s^2 for other water depth ratios. Figure 7 shows the acceleration response for the excitation frequency ratio of 1.0. In this case, the maximum acceleration of the structure without TLD has been observed as about 5.5 m/s^2 , which is reduced to about 1 m/s^2 for the water depth ratio of 0.05 and within the range of 0.5 and 0.7 m/s^2 for other water depth ratios. A similar trend has been observed in Figure 8 which shows the acceleration response for the excitation frequency ratio of 1.05. Here, the maximum acceleration of the structure without TLD is found at 2 m/s^2 , which is reduced to about 0.8 m/s^2 for the water depth ratio of 0.05 and in between 0.4 and 0.55 m/s^2 for other water depth ratios. Hence, from the mentioned observations, it is clear that the optimum control in peak acceleration for a particular frequency ratio is obtained with higher water depth ratios, and maximum reduction in response is obtained when the frequency ratio becomes unity.

Effect of tuning ratio on structural response

The tuning ratio of a rectangular TLD, as defined earlier, is the ratio of the fundamental linear sloshing frequency (f_w) to the natural frequency of the structure (f_s). By convention, a TLD implies that this tuning ratio is unity. However, earlier experimental studies have shown that the optimum response control is obtained when the tuning ratio is close to unity. Figures 9 and 10 show the comparison between response control of two rectangular tanks (TLD₁ and TLD₂) where the depth of liquid (90 mm for TLD₁ and 50 mm for TLD₂) in each damper is adjusted such that the fundamental sloshing frequency is

almost tuned to the natural frequency of the structure. The effectiveness of TLDs, ψ , is measured in terms of the reduction of structural displacement with TLDs compared to the corresponding value without TLDs:

$$\psi = \frac{(x_0 - x_{TLD})}{x_{TLD}} \times 100\%, \quad (2)$$

where x_{TLD} and x_0 are the peak displacement values with and without TLDs, respectively. Here, the effectiveness of TLD₁ and TLD₂ has been found as 53.1% and 34.6%, respectively. Therefore, it is observed that TLD₁ has better performance than TLD₂.

Conclusions

The present study focused on the implementation of a tuned liquid damper for mitigation of structural response. A set of experiments were carried out for studying the sloshing phenomenon in a rectangular and a square tank under harmonic loading condition. Different water depth ratios varying from 0.05 to 0.3 and several excitation frequency ratios varying from 0.75 to 1.3 were considered. The effect of tuned condition ($f_w/f_s \approx 1$) on structural response is also studied. The responses of two systems, that is, with and without TLD, are evaluated and presented in graphical and tabular forms. From this study, it has been observed that among all the water depth ratios for a given range of excitation frequency ratios, there exists optimum water depth that corresponds to the minimum response amplitude for each damper. These values are 7.5, 5 and 7.5 cm, respectively, for TLD₁, TLD₂, and TLD₃. It is seen that the square

TLD is less effective in comparison with the rectangular TLD for the controlling response of the structure.

At the initial stage, when the excitation frequency is lower than the resonance frequency, the peak structural response typically increases with increasing water depth ratio. However, at the region of resonance ($f/f_s \approx 1$), the response amplitude reduces drastically upon attachment of the TLD. Similarly, when the excitation frequencies become higher than the resonance frequency, no efficient control is observed. Thus, maximum control of response is obtained when the structure is subjected to resonance frequency, and the reduction of response, considering the resonance condition, is obtained at nearly 86.6% and 73.2% for TLD₁ and TLD₂, respectively. In case of tuned condition, the effectiveness of TLD₁ and TLD₂ has been found as 53.1% and 34.6%, respectively. Therefore, it is observed that TLD₁ has better performance in comparison with TLD₂. From this study, it has been found that TLD can be successfully used to control the response of the structure.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

EB prepared the experimental model, carried out the experiments and drafted the manuscript. LH had given the idea, participated in designing the experimental model, helped in the interpretation of experimental output and also helped in drafting the manuscript. RPS has guided during acquisition of data and also has checked the manuscript before submission. All authors read and approved the final manuscript.

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Received: 6 September 2012 Accepted: 28 January 2013

Published: 12 February 2013

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doi:10.1186/2008-6695-5-3

Cite this article as: Bhattacharjee et al.: An experimental study on tuned liquid damper for mitigation of structural response. *International Journal of Advanced Structural Engineering* 2013 5:3.

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